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NUCLEAR WEAPON R&D AND THE ROLE OF NUCLEAR TESTING

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Nuclear Weapon R&D and the Role of Nuclear Testing

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Nuclear Weapon R&D and the Role of Nuclear Testing

Our national policy with respect to nuclear weapons is one of deterrence. For deterrence to be a credible policy, the U.S. must maintain an effective, survivable, and varied nuclear force to convince any adversary that we could retaliate with nuclear weapons in the event of aggression against us or our allies.

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The global strategic balance is constantly changing. New technologies and developments can weaken the credibility and survivability of the U.S. deterrent; they may also enhance credibility and survivability. The tension between these two effects leads to a dynamic deterrent relationship among nations. In turn, this can lead to changes in mission requirements for our nuclear forces or to changes in delivery systems, which might require the modification of existing nuclear warheads or the development of new warheads.

For example, Soviet missile accuracies are constantly improving, putting our land-based missile force at ever greater risk from an enemy first strike. Some day, the Soviets may develop the capability to achieve even greater accuracy by using satellites to provide terminal guidance for their warheads. We can use a number of technological solutions to enhance the survivability of our land-based missiles, some of which are new systems that require new warheads. For example, we might develop a ballistic missile defense system to protect portions of our land-based missiles, thereby ensuring that enough missiles would survive a first-strike attack to provide a retaliatory capability. Hardening our missile silos, deceptive basing, and deploying mobile land-based missiles are other solutions.

The mobile small intercontinental ballistic missile (SICBM), sometimes called the Midgetman, is a mobile system that is currently of great interest to the defense community (Fig. 1). To enhance its mobility and increase its survivability, the SICBM must be lightweight, which, in turn, limits its throw-weight (payload) capability. Because the SICBM may have to travel over rough roads or cross country, its warhead must be designed to withstand long-term vibration environments. In addition, because of potential access by the public to deployment areas, its warhead must have appropriate safety and security features. There is also an ongoing debate as to how large the SICBM should be and whether it should carry a single or multiple warheads. The ultimate choice of a warhead for the SICBM awaits resolution of this debate.

The choice of warhead for the SICBM illustrates some of the considerations involved in the acquisition of a new weapon system. The Department of Defense (DOD) specifies the requirements for the new mission and new delivery system. The Department of Energy (DOE) weapons design laboratories (Livermore and Los Alamos, in collaboration with Sandia) are asked to state how they would meet the warhead requirements for the new system. Sometimes it is possible to meet the requirements by modifying warheads from existing systems, but, more often than not, a new warhead is required. (Warhead development and production costs are typically only 10 to 15% of the total cost of the delivery system.)

The weapons design laboratories also have the continuing responsibility to research new technologies that might improve our deterrent capability or even alter our approach to deterrence. On occasion, they conceive new concepts or pursue novel physics principles that have potential application to new weapon systems. If the proposed concepts have merit, they may eventually be developed into an actual weapon system.

A significant motivation for exploring new concepts is to avoid technological surprise and to find out what is possible in weapons technology. If a new technology is possible for the U.S., then it is also possible for others. Our deterrent posture would be jeopardized if our adversaries were to develop a new and particularly threatening capability that put at risk a large fraction of our deterrent capability. For example, LLNL is engaged in an active research program to study nuclear-driven directed-energy weapons, such as the x-ray laser, in support of the Strategic Defense Initiative (SDI). A most important reason for doing this research is to assess the threat that U.S. space-based defenses and other military space assets might face should the Soviets deploy such a weapon.

Once the requirement for a new weapon system is spelled out, the DOE design laboratories undertake extensive studies to determine its feasibility (see the article on p. 19). After feasibility is established, a complex iterative process ensues, involving the legislative and executive branches of the U.S. government, before approval is finally granted for the development and ultimate production of the weapon.

Military Characteristics of a Warhead

The DOD prepares a set of military characteristics (MCs) that defines the requirements for the nuclear warhead. The MCs specified

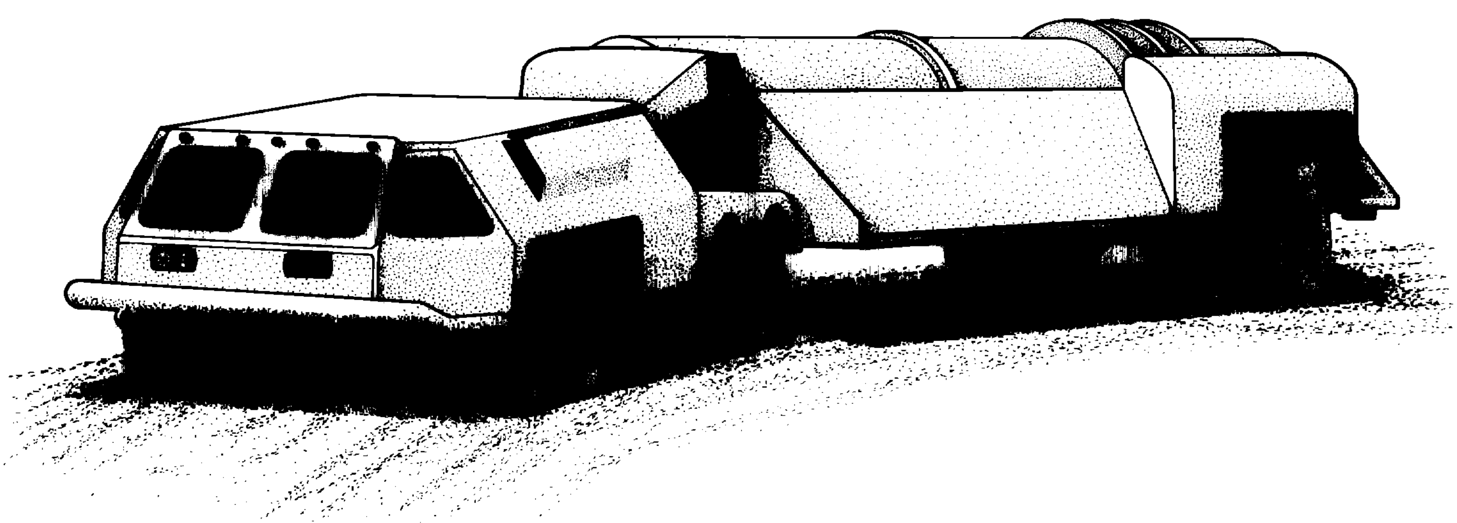


Fig. 1

The survivability of our strategic forces will be improved by deploying small intercontinental ballistic missiles (SICBMs) in hardened mobile launchers. An attack on hardened launchers, dispersed over a large area, would require an unfavorable exchange ratio to achieve high confidence in destroying a significant fraction of these targets.

for the warhead for the Peacekeeper missile are typical:

- Nuclear safety (e.g., no nuclear yield in an accident and positive measures to prevent inadvertent arming and firing).
- Size and weight of DOE-designed components to ensure compatibility with the specified reentry vehicle.
- Plutonium dispersal safety in case of an accident.
- Operational reliability.
- Yield.
- Conservative use of nuclear materials (e.g., plutonium, tritium) to minimize cost.
- Minimum maintenance.
- Operational simplicity.

The DOD requires that, in the event that compliance with these MCs leads to a design conflict, priorities shall be observed in the order listed above, giving consideration to tradeoffs that allow high-priority MCs to be attained while minimizing the degradation of the competing, lower-priority MCs. The final quantitative values for the MCs are often arrived at through an iterative process between the DOE and the DOD. The design laboratories determine what is technically possible, and the DOD and the DOE then come to mutual agreement as to the appropriate tradeoffs to minimize the overall cost of the weapon system while maximizing the system's capabilities.

We have always been concerned about warhead endurance and replicability, but tradeoffs to achieve other weapon features have previously been paramount. In 1982, the DOD added a paragraph concerning warhead endurance and replicability to the MCs in which these two features are described to be desirable goals consistent with meeting the other MCs. For the Peacekeeper warhead, this paragraph states:

"It is desired that the warhead have an inherent endurance obtained as a result of design considerations that address: a maximum warhead lifetime, maximizing the ability to replicate the warhead at a future date, and maximizing the ability to incorporate this warhead in other weapon delivery systems. Therefore, the design, development, and production of the warhead must be well documented and involve processes that to the extent possible allow replication at a future date."

Stockpile Endurance

The LLNL weapons in the stockpile and those we are currently developing have been designed to be as conservative as possible with respect to the adverse effects of aging within the constraints of the MCs. Correcting a problem in the stockpile is extremely expensive and time-consuming. The need for such actions is minimized by taking appropriate care when a weapon is designed and before it enters the stockpile. Scientists and engineers strive to make their designs durable and robust against all foreseeable stockpile conditions. Even so, situations have arisen with stockpiled weapons that have brought into question their continued endurance and reliability. Nuclear tests have been required to identify and, in a large number of cases, to resolve these problems. We have not been able to predict or preclude all of the problems that have occurred, and thus we believe that continued nuclear testing is essential to guarantee the viability of the stockpile.

If stockpile endurance were the highest priority or the only priority, it is likely that the designs would have been different. The warheads probably would have been larger and heavier and would have contained more nuclear material. We might also have forgone many stockpile improvement features involving enhanced safety and security that tend to increase warhead sensitivity to stockpile aging. Changes in priorities could have led to very different military systems—missiles or other platforms with different throw weights, ranges, accuracies, and operational flexibility. In addition, the economic impact of a different set of priorities would have been substantial.

Replicability

It is often argued that we should simply replicate a weapon according to its original design specifications when a serious stockpile aging problem is discovered. While replication of a defective weapon component may sometimes be a way to fix a problem, such replication is never exact and may not be easily achieved, cost-effective, or desirable.

Modern weapons are designed using the most durable and easy-to-manufacture components that do the job. In principle, past designs could be replicated with varying degrees of difficulty, depending on when the weapon entered the stockpile. The problem, however, is analogous to trying today to replicate a 1950-vintage vacuum-tube television set.

Construction of a device to a specific set of blueprints is not sufficient to guarantee proper performance; the actual production item must be tested. This situation is particularly true when dealing with an older technology for which the scientific expertise may be significantly dispersed. We just do not have the ability to understand and specify all the factors that affect nuclear device performance.

The problems that make replication difficult in practice are changes in technology and increasingly stringent U.S. health and safety standards. Most of the technology changes produce better products and improved performance. Changes also occur because U.S. industry introduces new product lines and discontinues others. Experience has shown that it is virtually impossible to prevent changes in materials, processes, and workmanship quality and standards, and even in specifications and working drawings over extended periods of time. Changes in technology are particularly rapid in the electronics industry, making it virtually impossible to replicate the electronic systems used to detonate earlier nuclear weapons.

A fundamental issue with replication is the inevitable need for future weapon scientists, who might lack the necessary expertise, to make decisions as to whether changes can be made in the production process without adversely affecting the performance of the weapon. The challenge faced by the weapon designers, therefore, is to develop warheads that minimize the possibility or impact of mistakes in future versions of the design.

The availability of organic materials changes with time. Some compounds have been found to be carcinogenic and are no longer produced. Other product changes occur as a result of economics and product improvements. High explosives are an example of organic materials that are particularly difficult to replicate. We may not be able to reproduce the older production processes for the explosive, some of which involve as many aspects of art as they do of science. Replacing an older explosive with a new one is actually a significant design change that requires nuclear testing.

The chemically reactive nature of many components used in nuclear weapons sometimes results in chemical incompatibilities that can lead to early degradation in the stockpile. New technology, instead of replication, often allows designers to use fewer nuclear materials or alternate materials or to relax certain specifications to reduce costs. However, some of these changes may need to be verified in a nuclear test, and expert scientific judgment is required to determine which changes can be safely made without nuclear testing and which require nuclear tests.

Identical replication of a troublesome system would also invite recurrence of a given problem. The fact that modern safety and security features are not present in older systems is noteworthy. The rejuvenation of an older system presents an opportunity to add these important features to the stockpile. Exact replication would preclude improvements in the design or fabrication of a weapon, even though the reasons advanced for such improvements are often driven by compelling economic factors or by safety and security considerations. Such improvements often involve design changes that affect the performance of a weapon, requiring a nuclear test for certification.

Finally, we have found through experience that we cannot specify all the subtle manufacturing criteria that affect nuclear weapon performance. Nuclear proof tests are required to verify the manufacturing process for the weapon. Proof tests are especially important when production of a warhead lasts for many years, during which time subtle changes can creep into the manufacturing process. In a recent example, the use of preproduction hardware with specifications identical to those to be used in the production line, but tailor-made for a nuclear test, significantly affected the yield of a nuclear device at the Nevada Test Site (NTS).

Modernizing for Improved Safety and Survivability

The safety and security record of the U.S. stockpile is excellent. This success is due, in large part, to our continuing efforts to design safe and survivable warheads and to modernize the stockpile by incorporating new safety and security features into new and existing weapons. Only one-third of our stockpiled weapons have these modern safety and security features.

Safety

No weapon accident has ever produced any nuclear yield. In two accidents, however, the high explosive in the weapons reacted violently, dispersing plutonium in the vicinity of the crashes. In 1966 a B52 bomber carrying nuclear weapons crashed in Palomares, Spain, and in 1968 another crashed in Thule, Greenland. At Palomares, the high explosive detonated; at Thule, evidence indicates that the explosive underwent deflagration or rapid burning. Because the devices had been designed and tested to be safe against high-explosive initiation at a single point, there was no nuclear yield. However, cleanup of the plutonium to acceptable levels was extremely expensive, and the political consequences of these accidents were quite serious.

Until these two accidents occurred, it was possible for our B52 bombers to remain on continuous airborne alert. However, in part because of the plutonium dispersal experienced at Thule and Palomares, it was deemed that the risk of plutonium dispersal was too great, and continuous airborne alerts were discontinued.

In September 1980, a B52 caught fire on the tarmac at an Air Force base in the continental U.S. Figure 2a is a photograph of the burning B52 taken at night; Fig. 2b shows the aircraft in the morning after the fire was extinguished. The fire occurred in one of the engines while the wind was blowing away from the fuselage of the plane, as shown by the blackened mark on the runway. Had the wind been blowing toward the plane (the normal wind direction for that time of year), the fuselage would have caught fire.

Our B52 bombers are normally parked in "strip alert" on similar tarmacs at various Air Force bases. These bombers carry live bombs and short-range attack missiles containing a type of sensitive high explosive similar to that involved in the accidents at Thule and Palomeres. If these planes were to catch fire, it is possible that either the explosive in the bombs would detonate and burn or that the weapons would be damaged in the fire. In either event, plutonium dispersal would be a threat.

To avert such problems, Livermore and Los Alamos scientists developed a new explosive, TATB or triamino-trinitro-benzene, that is now entering the stockpile in a variety of weapon systems. TATB is an insensitive high explosive (IHE) and is extremely difficult to detonate in the event of an accident, such as the impact of a stray bullet or an airplane crash. Its use would have precluded plutonium dispersal in the Thule and Palomares accidents.

Another instance illustrating the dangers of potential detonation occurred with a Titan missile in Damascus, Arkansas, in September 1980, when the rocket propellant in a Titan missile exploded (Fig. 3). The warhead was thrown clear of the missile and, fortunately, the high explosive (conventional, not insensitive) did not detonate. The Titan missile is now being retired. The new Peacekeeper warhead will have IHE and thus will not be vulnerable to such an accident, illustrating again the importance of weapon modernization.

Survivability

The SICBM, the ground-launched cruise missile (GLCM), and the air-launched cruise missile (ALCM) are examples of weapon systems that provide greatly increased survivability to enemy attack. The GLCM and ALCM, with warheads designed by Livermore and Los Alamos, respectively, are now in stockpile. The SICBM is still in development.

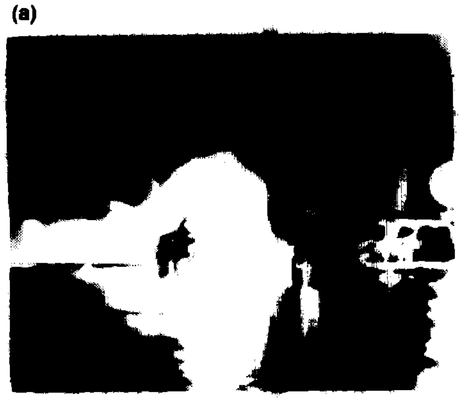
In the GLCM and the SICBM, survivability is enhanced by mobility of the weapon. This mobility requires that both warheads use IHE to provide safety. The ALCM warhead also uses IHE. The ALCM is carried by our B52 and B1 bombers; it enhances the survivability of our second-strike force by allowing the bombers to launch their weapons before they encounter Soviet air defenses.

The GLCM warhead also has enhanced security features that deny use of the weapon should it fall into enemy or terrorist hands. The GLCM and the Peacekeeper warheads also have features that increase their safety in the event of a fire. These features retard possible damage, allowing more time to extinguish the fire and thereby reducing the risk of plutonium dispersal.

Survivability and Nuclear Effects Testing

A very important part of the U.S. nuclear testing program, and a responsibility of the Defense Nuclear Agency, is to test the effects of nuclear weapons on a vast array of military equipment. Of particular concern are the nonnuclear components of our

(a)



(b)

Fig. 2

In September 1980, a B52 sitting on the tarmac caught fire at an Air Force base in the continental U.S. (a) The burning B52 at night. (b) The same B52 on the morning after the fire in one of the engines had been extinguished. The wind was blowing away from the fuselage, as shown by the blackened area on the runway. Had the wind been blowing in the direction normal for that time of year, the fuselage probably would have caught fire. Our B52 bombers are usually parked in "strip alert" at similar bases. If the planes were to catch fire, the high explosive in any bombs on board could conceivably detonate or burn, which, in turn, might lead to plutonium dispersal. The use of insensitive high explosive can eliminate the hazards of such plutonium dispersal.

strategic weapon systems, warning sensors, and communications equipment which might have to function in a nuclear environment. As in the testing of nuclear weapons, we are frequently surprised by the results of nuclear effects tests on equipment that has previously been subjected to nonnuclear tests. Often, the nuclear tests reveal changes that must be made, and additional nuclear tests usually are required to certify the survival and proper functioning of these systems in a hostile nuclear environment.

Reduced Stockpile Yield and Number of Weapons

It is often erroneously believed that efforts to modernize the U.S. nuclear stockpile have led to an escalating yield and number of weapons. In fact, the exact opposite is true. Figure 4 shows the relative total yield of the U.S. stockpile from 1955 through 1985. This figure reveals that the total yield of the U.S. stockpile has been reduced fourfold from its peak value in the mid-1960s. Modernization has played a major role in reducing the yield of the stockpile. This reduction is largely the result of increased accuracy of the delivery systems, which has made it possible to develop and deploy warheads of lower yield. Figure 5 shows the relative number of U.S. nuclear weapons versus time; the number of weapons in the stockpile at the end of 1985 is about 25% lower than the peak value.

LLNL's Weapons Program

As one of the nation's two nuclear design laboratories, LLNL plays a vital role in designing and maintaining the U.S. nuclear deterrent. As can be seen from the discussions above, the responsibilities and challenges involved are significant. To meet them, the Laboratory's Weapons Program has defined four broad missions.

The first and most important is to ensure that the weapons in the stockpile and those now entering the stockpile are safe and reliable. We have responsibility for monitoring the LLNL-designed weapons in the stockpile. Confidence in the reliability of the weapons in the stockpile is maintained by the stockpile surveillance program, by quality assurance and reliability testing of nonnuclear components, and by nuclear testing of warheads or related devices. Laboratory weapons scientists conduct about two stockpile confidence tests each year, during which either war-reserve components or weapons from the field are returned for testing at the NTS. These tests are not merely simple experiments to verify yield; rather, the devices are thoroughly diagnosed to identify potential problems that could affect the physics performance of the weapon. Serious stockpile problems have been revealed by these tests, and nuclear tests have been required to resolve them.

The second mission is to develop warhead options for new weapon systems. In developing warheads to meet DOD's requirements, we place considerable emphasis on improvements in safety, security, survivability, and military

(a)

(b)

Fig. 3

In Damascus, Arkansas, in September 1980, the rocket propellant in a Titan missile exploded, throwing the warhead clear of the missile. The aerial view (a) and photograph of the silo doors (b) reveal the force of the explosion. Fortunately, the high explosive in the warhead did not detonate. The Titan is now being retired, and there will no longer be a risk from this weapon system. The warhead in the new Peacekeeper missile contains an insensitive high explosive and will be invulnerable to such an accident.

effectiveness. A number of nuclear tests are conducted each year as part of our ongoing weapon development program. These tests also contribute to our stockpile maintenance efforts by providing actual experience for scientists who must make judgments about the stockpile and by adding to our data base of nuclear device performance.

A third mission is to maintain expertise in the area of nuclear weapon design and development. This enables us to improve our understanding of current weapon systems and provides a technology base for future options as dictated by national security needs. Weapons expertise is of great importance in providing insight into what is technologically possible for our potential adversaries. Experienced personnel are essential to this effort. Many design and stockpile reliability decisions rely heavily on the technical judgment of the weapons scientist, judgment that can be derived only from experience.

The fourth mission of the Laboratory's Weapons Program is to provide technical support for the nation's objectives in arms control and verification. Arms control is not a separate effort at LLNL; rather, it is an integral part of the Weapons Program. The same expertise that is used to develop weapons is directly applied to their control. We regularly serve as advisors to various national and international committees on the technical merits and verifiability of arms control proposals, and we perform technical studies on issues related to arms control, national security, and arms race and crisis stability.[1]

Nuclear Testing and Stockpile Reliability

Nuclear weapons are complex mechanisms made of highly reactive materials and sometimes, of necessity, they include materials with limited lifetimes. Because of these characteristics, changes have occurred in stockpile weapons that raise the question of whether a weapon would perform as designed. Figure 6 shows a weapon part in which extensive corrosion was observed during routine stockpile surveillance. In this case, designers determined that the corrosion would not adversely affect the operation of the weapon. They were able to make this assessment with confidence because they had developed technical judgment based on years of experience in conducting nuclear tests that permitted them to evaluate what factors mattered.

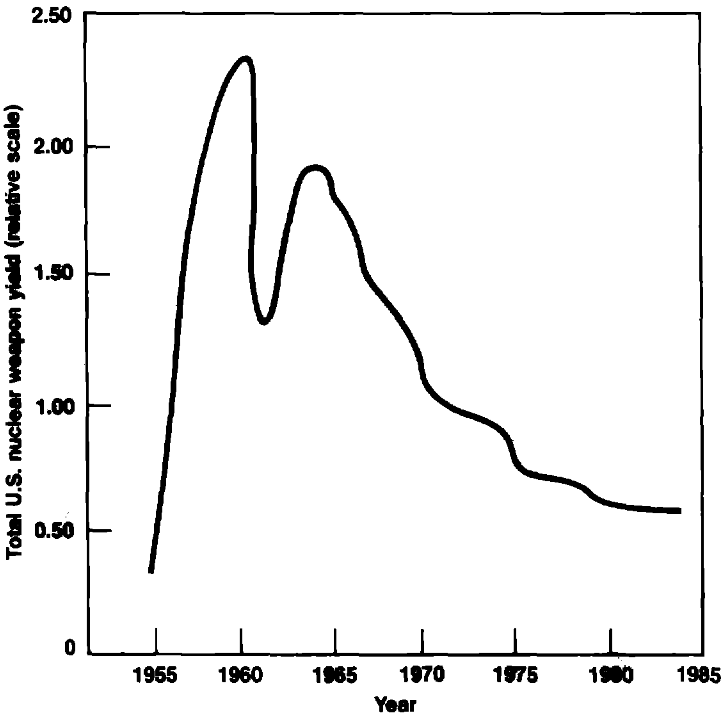


Fig. 4

Total yield of the U.S. nuclear weapon stockpile (relative to a value of 1.0 for the year 1972) from 1955 through 1985. This curve shows that the total yield in the stockpile has been reduced fourfold from its peak value in the mid-1960s, demonstrating the role that modernization has played in reducing the yield of the stockpile.

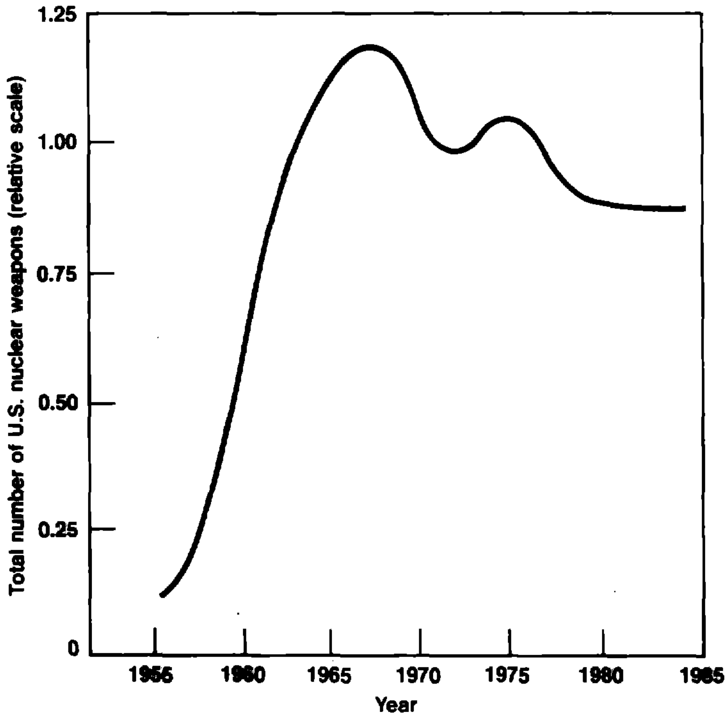


Fig. 5

The number of total U.S. nuclear weapons in the stockpile inventory (relative to a value of 1.0 for the year 1972) from 1955 through 1985. The total number of weapons in the stockpile at the end of 1985 was 25% lower than the peak value in the 1960s. These data demonstrate that, contrary to the commonly held belief, modernization has led to fewer total nuclear weapons in the stockpile.

Nuclear tests, however, have been necessary to fix problems. Approximately one-third of all modern weapon designs placed in the U.S. stockpile required and received post-deployment nuclear tests for resolution of problems. In three-fourths of these cases, the problems were discovered only because of the ongoing nuclear testing. A number of problems arose because of the nuclear test moratorium of 1958–1961, clearly illustrating the difficulties that can arise in the absence of nuclear testing.

Lessons from the Test Moratorium

From 1958 to 1961, the U.S. and the Soviet Union observed an unwritten agreement not to test nuclear weapons. In effect, there was a *de facto* test ban for three years. However, in September 1961, the Soviets suddenly resumed testing with an extensive and well-prepared series of events, surprising us by the extent of their test series and the magnitude of their yields. The U.S. followed suit as best it could, but testing initially was on a very limited scale and required a long time to come up to speed.

The U.S. experienced a number of surprises when certain weapon systems developed during the moratorium failed to perform as predicted when they were finally tested. The failures were due to such factors as a lack of understanding of the fundamental physics of nuclear explosives, inadequate knowledge of the environments in which weapons might be required to survive, improper approaches to weapon safety, and, most important, unjustified confidence bred by nonnuclear experimentation and unverified calculations. If testing had not resumed, some of the warhead designs that entered the stockpile would not have worked.

Problems with the W52 High Explosive. The W52 was the nuclear warhead for the Army's now-retired Sergeant surface-to-surface missile. In 1959, a warhead was being readied for production when two explosive accidents occurred at Los Alamos, killing four people. The explosions were due to the unexpected susceptibility to accidental detonation of the high explosive used in the W52's fission trigger.

Los Alamos had to change the explosive used in the W52 to a safer and less sensitive explosive, which was also somewhat less energetic. This decision was made during the moratorium, when the new design could not be verified in a nuclear test. The redesign was based on nonnuclear hydrodynamic tests and on computer design calculations.

Because of the high confidence that Los Alamos scientists had in their redesign, they did not immediately test the W52 when the moratorium ended in 1961. The W52 entered the stockpile in April 1962. When Los Alamos finally tested the device in early 1963, the W52 gave only a small fraction of its expected yield. The weapon, as delivered, was militarily unacceptable.

Los Alamos scientists made a rapid redesign. Within three months of the test failure, they successfully conducted a nuclear test of the new design, which was subsequently incorporated into the stockpile. The difficulties with the W52 are an especially dramatic illustration of the limitations of nonnuclear experiments and computer calculations in the evaluation of seemingly moderate changes in warhead designs.

Unexpected Aging in the W45. LLNL scientists developed the W45 in part during the moratorium. The W45 was the warhead for the now-retired Little John missile and atomic demolition munition (ADM); the W45 is still used in the Terrier missile. When the W45 entered the stockpile in 1962, it had not been tested to simulate certain effects of stockpile aging. Because of confidence in our calculations and other priorities, we waited until the mid-1960s to test the effect of what we expected to be small aging changes. The result was a surprise: the test gave only one-half the expected yield.

Design changes were made to the W45, and these were verified in a series of five nuclear tests. It was only on the basis of these tests that we

Fig. 6

Extensive corrosion was observed in this weapon part during routine stockpile surveillance. In this example, LLNL designers determined that the corrosion would not adversely affect operation of the weapon. They were able to make this assessment with confidence on the basis of technical judgment developed over years of experience in conducting nuclear tests.

could guarantee the performance of the various versions of the W45 at different stockpile ages.

Los Alamos also had similar problems with aging that affected a number of stockpile designs. These problems have been corrected, but nuclear testing was essential to their resolution.

Problems with More Modern Weapon Systems

Although the problems with the W52 and W45 arose at the time of the test moratorium, even modern weapon systems have had problems that have been identified and resolved only by nuclear testing. In one case, deterioration of a weapon component was observed during normal stockpile surveillance, and the weapons designers judged the problem to be serious enough to require a design modification. The component was redesigned and a nuclear proof test was required to certify that the new design would perform properly.

In another case, a final proof test of a stockpiled weapon, tested under certain aging conditions to be expected in the stockpile, gave an unexpected reduction in yield. The weapons designers suspected that various engineering design features incorporated in the weapon after the physics-design nuclear tests were successfully completed may have had an adverse effect on the operation of the weapon. Design changes were made, and a second proof test was conducted to verify that the weapon would meet its military requirements.

In a third case, a final proof test at the weapon's specified low-temperature extreme was done just after deployment of the weapon had begun. The test results were a complete surprise. The device gave only a small fraction of its expected yield. The weapon had been tested extensively in nonnuclear hydrodynamic tests and was even tested at the low-temperature extreme with no indication of trouble. Thus, on the basis of the nonnuclear testing and previous successful nuclear tests, the weapons designers had every reason to believe that the low-temperature proof test would produce the predicted yield. After extensive post-test analysis, the design was modified and another low-temperature nuclear test was performed. The test of the modified design was successful, and confidence was established that the warhead would operate properly over its entire temperature range. The production specifications were changed, and the approved warhead entered the stockpile.

This last example illustrates yet again the inadequacy of nonnuclear testing and the need for nuclear tests. Without the low-temperature nuclear test, the weapons designers would have judged, on the basis of the nonnuclear tests, that the system would perform properly. However, in actuality, the deterrent capability of this particular weapon system would have been in question under environmental conditions that could have been fully expected to occur. As a result of the experience with this particular warhead, similar low-temperature nuclear tests have been done for several other weapon systems.

Nuclear Testing and Weapon Design

The design of a weapon is a complex, iterative process. We start by simulating experiments on high-speed computers. However, such simulations encounter difficulties in matching the real behavior of a nuclear device, in part because of their use of a largely theoretical and phenomenological data base that contains considerable uncertainties.

Nuclear explosions involve extreme conditions—temperatures of millions of degrees, velocities of millions of kilometres an hour, and time scales as short as a few billionths of a second. The physical conditions in a nuclear explosion simply cannot be simulated in full extent or detail in nonnuclear experimental facilities. Accordingly, we must verify our calculations with actual nuclear tests.

A successful nuclear test of a physics device is not equivalent to successful development of a new weapon. A physics device is not a weapon. A weapon must be able to withstand extreme accelerations and environmental conditions. It must have structural supports, arming and firing mechanisms, and engineering design features that can significantly alter its physics behavior. Indeed, our experience with nuclear tests indicates that seemingly unimportant factors, such as chemical impurities, joints and other fabrication features, temperature extremes, and aging effects, can have a major effect on the behavior of a weapon.

Future Directions in Weapon Design

In addition to improved safety, security, and survivability, increased military effectiveness is another major concern in the development of new weapons. Several new weapon concepts are currently being investigated at LLNL that could provide substantial benefits to the U.S. deterrent capability.

Earth-Penetrating Warhead

The earth-penetrating warhead (EPW), shown in Fig. 7, can provide a greatly improved capability for destroying hardened military targets with substantial reductions in yield. It has been argued that hard-target capability can be destabilizing. However, such capability can have considerable deterrent value when it holds at risk assets that an adversary highly values.

By penetrating a short distance into the ground before it detonates, the EPW couples a much greater fraction of its nuclear yield into ground motion. To deliver a given shock-wave intensity to an underground target, an EPW requires considerably less yield than a surface-burst weapon. Although for a given yield, the EPW is heavier than a surface-burst warhead, since it must be robust enough to withstand the intense stresses of earth penetration, the overall gain in the military effect for a given warhead weight is substantial.

Nuclear Directed-Energy Weapons

Other new weapon concepts include nuclear directed-energy weapons (NDEW), such as the x-ray laser. These weapons are being developed in support of the Strategic Defense Initiative (SDI). Although the primary SDI emphasis is on nonnuclear defensive weapons, it is important to understand what can be achieved with NDEWs. The most important reason for doing research on NDEWs is to assess the threat that U.S. systems might face from the Soviets, should they deploy such a weapon. For example, available evidence indicates that the Soviets have had a very active x-ray laser research program, although we do not know if they have succeeded in developing an effective x-ray laser weapon. NDEWs like the x-ray laser might be extremely capable as a counter to space-based defenses or other military assets in space, and it is important to determine what is technologically possible in this area.

In addition, although it is desirable for a defensive system not to rely on nuclear weapons, NDEW concepts serve as a hedge in the event that nonnuclear technologies are not successful. NDEWs could have a significant advantage because they employ the most concentrated energy source available and have advantages in weight and launching costs.

NDEWs can provide a useful complement to nonnuclear defensive weapon deployments. Nonnuclear defensive weapons, which attack targets sequentially, are most stressed by salvo attacks, in which their ability to rapidly acquire, track, and destroy targets is strained. NDEWs, however, are expected to have much higher intensities than nonnuclear directed-energy weapons plus the capability to attack many targets simultaneously. Accordingly, NDEWs force the enemy to spread out its offensive. The result is similar to that achieved by tactical nuclear weapons in Europe, where their possible use deters the massing of conventional Soviet forces, thereby enhancing the ability of conventional defenses to defeat an aggressor.

Nuclear Testing and Technical Judgment

Our experience with the 1958–1961 testing moratorium highlights the uniqueness of the overall process of weapons design and certification. Certification is a guarantee that the weapon will meet the DOD-specified military characteristics. Weapons designers cannot certify nuclear performance on the basis of nonnuclear experiments alone. They cannot model with computers all of the complex physical processes to be able to predict nuclear warhead performance with confidence. Nuclear warheads cannot be "thoroughly" or statistically tested. As a result, the functional capabilities of nuclear explosives cannot be fully established without resorting to a strong dependence on the scientific judgment of the weapons designer.

Assessment of a weapon design rests ultimately on scientific judgment based on nuclear test experience. This judgment takes considerable time to develop, is cultivated by the application of theory and calculation to device design, and is continually refined on the basis of data from nuclear tests. Removing the confirmation provided by test results, as happened in 1958–1961, results in the overextension of judgment and in reduced credibility of the nation's deterrent.

Because of the large number of nuclear tests that would be required, it is not feasible to obtain statistically significant data on a given nuclear system. The variability of a system's nuclear performance with changes in production tolerances, environmental

Fig. 7

Photograph of a mock earth-penetrating weapon (EPW) fired from a cannon into the ground at Site 300. The structural integrity of the warhead has been maintained despite the intense stresses experienced by the warhead during penetration into the ground.

conditions (e.g., temperature extremes), hostile environments (as are encountered in antiballistic missile engagements), and aging effects must be simulated with analytical, computational, and phenomenological models. The relevance and completeness of such models are based on the professional judgment of scientific personnel involved in the actual physics, design, and analysis of nuclear warheads. This judgment is aided and constrained by experimental data from testing actual nuclear devices and by data from physics experiments at NTS in the applicable temperature and density regimes. Significant amounts of physics data are derived from actual nuclear tests.

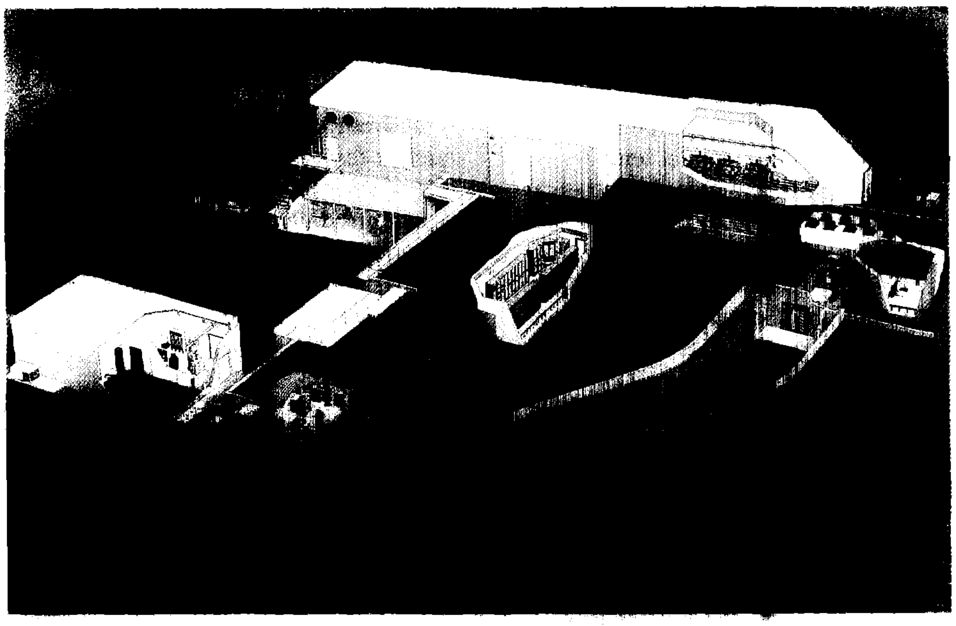
Preparations for a Cessation of Testing

The U.S. policy of deterrence is based on reliable and effective nuclear weapons. A long-term cessation of nuclear testing would place that deterrent capability in jeopardy. Even under such conditions, however, the Laboratory would have to do its best to ensure the reliability of the nuclear weapons. Accordingly, we have long been concerned with how we could carry out our responsibilities under treaty limitations such as those proposed for a comprehensive test ban (CTB).

Since the 1958–1961 nuclear test moratorium, the Laboratory has been aware of the potential impact of a CTB. Assessments by the Laboratory of the consequences of a CTB have been requested by the U.S. government on many occasions. What will be the Laboratory's ability to carry out its responsibilities if testing is prohibited? It seems likely that, at the very least, these responsibilities will include ensuring the reliability of the existing stockpile, assessing changes in weapons caused by stockpile aging, and assessing corrections of potential problems. It also appears likely that under such a ban, many of our responsibilities could not be met.

We have already discussed changes in weapons design that are dictated by safety and security considerations, use of new materials, new configurations, or new military requirements. Not all such changes require certification by full-scale nuclear tests, but all rely on data obtained in nuclear tests and, most critically, on the judgment and insight that scientists and engineers acquire on the basis of such data. Under a CTB, experimental data could no longer be obtained from testing, the pool of experienced specialists would decline, and the skills of those that remain would diminish.

(a)



(b)

Fig. 8

Overall view of the FXR facility (a), showing the control room, the electronics corridor, the electron source, the chain of accelerator modules, the tungsten target, the firing table and film cassette, and the optics room in which optical records of the implosion are made. The interior of the FXR facility (b), showing the electron beam pipe and beam accelerator modules. The FXR produces fast, intense x-ray pulses that yield high-resolution photographic images of rapidly moving parts inside dense, imploding devices. The devices tested at Site 300 contain inert (nonfissile) material. A goal of our research with the FXR is to gain information during the implosion of a device to complement similar information gathered from nuclear tests.

There is no satisfactory way to solve these problems. They may be alleviated to some extent by such measures as:

- Improving our understanding of present nuclear designs, including such basics as equations of state, opacities, radiation transport, and instabilities, by current nuclear tests and other means.
- Placing increased emphasis on the use of supercomputers and numerical models and on the vigorous development of advanced computers.
- Taking deliberate steps to maintain the capability to produce old weapon designs.
- Acquiring experimental facilities to augment our current nonnuclear testing capability.
- Designing weapons that would be even less likely to suffer material degradation than current designs or that could be modified if need be with less uncertainty about performance. There would, of course, be costs in weight, size, use of special nuclear materials, and military effectiveness with such designs.

The first three approaches are being pursued vigorously. We regularly conduct weapons physics experiments at the NTS as part of nuclear tests scheduled for other purposes. Since 1981, one or two LLNL tests per year have been dedicated to weapons physics research. The knowledge gained from these tests has already permitted us to develop more conservative and reliable designs. We are pursuing weapons physics programs using our experimental facilities at Site 300. In addition, the flash x-ray (FXR) facility (Fig. 8) and the Nova laser facility (Fig. 9) have greatly augmented our nonnuclear testing capabilities.

The Laboratory is constantly acquiring the most advanced supercomputers available. The Livermore Computer Center currently has two CDC 7600 computers, four Cray-1 computers, and one Cray-XMP/48. Much research is devoted to developing improved computational methods to make optimum use of advanced computer architectures and to improve the accuracy of the physics models in our weapons design codes.

Scientists are constantly challenged by the need to understand theoretically the complex physical processes they observe, and ordinarily this drive would be sufficient justification for doing research. Such an understanding is not necessarily essential to guarantee the continued reliability of nuclear weapons, so long as nuclear testing is possible. However, in the absence of nuclear testing, accurate theoretical understanding becomes even more important and provides the major motivation for the research.

In order to maintain the capability to remanufacture weapons, we are placing major emphasis on 25-year objectives, materials compatability, and engineering durability. We also rigidly document production procedures and materials. We could implement further steps, such as continuing production of older weapons at a low rate.

Repeated examination of various nonnuclear experimental facilities has not revealed any that could take the place of nuclear testing. Facilities that we can now envision for the future do not come close enough to simulating the conditions in a nuclear explosion. However, they can provide some relevant weapons physics data, help experimenters maintain some level of relevant skills, and provide a test bed for weapons designers to verify some theoretical aspects of weapons physics.

Examples of existing facilities that would be of some use in the event of a CTB include the FXR and other facilities at Site 300 as well as the Nova laser. We expect, however, that

Fig. 9

In the Nova laser target chamber (4.6 m in diameter), ten laser beams converge on a tiny capsule of thermonuclear fuel, heating and compressing it until it ignites in a fusion reaction. This facility has been used to simulate some aspects of a nuclear explosion. However, existing facilities and those we can envision for the immediate future cannot simulate in sufficient extent or detail the physical conditions present in an actual nuclear explosion.

major expensive extensions of these facilities would be required to significantly enhance our ability to make judgments on the basis of nonnuclear testing alone. We are also constructing the High-Explosive Applications Facility (HEAF), which will provide a valuable test bed for high-explosive research. A High-Gain Test Facility (HGTF), using a multimegajoule laser for research on inertial confinement fusion (ICF), would provide much more intense conditions than those available with the Nova facility. The HGTF would allow us to make studies on 1000-MJ ICF capsules. Such yields would produce conditions that would be more relevant to some aspects of nuclear weapons design and diagnostics and would provide a source for some tests on military vulnerability, lethality, and exposure.

A current research program that would help to maintain skills is the development of advanced conventional munitions. Work on such munitions uses many of the same technologies (particularly hydrodynamics, material science, high-explosive chemistry, and high-speed diagnostics) that are involved in development of the fission triggers for nuclear weapons.

The last approach often mentioned to alleviate the impact of a ban on nuclear testing would be to design and manufacture weapons that are less likely to suffer degradation. This would be expensive and quite difficult to pursue because of the configuration of the present stockpile and delivery systems. For example, larger fission triggers are seen by some as less demanding. However, incorporating them in a weapon system would force the concomitant design and use of larger, more expensive missiles and submarines. Thus, there would have to be changes in the priorities of the MCs for future weapon systems. In addition, as history has shown, we often cannot judge ahead of time which components will degrade.

If the specified military characteristics were to change, we might be forced to give up certain improvements in weapons technology that have led to advances in safety, security, survivability, and military effectiveness. Without conducting a detailed study of each proposed new weapon system, we could not know what specific technological improvements would have to be sacrificed in any one system. For example, we might forgo the use of IHE in favor of conventional high explosive. Because IHE is more difficult to detonate, systems that employ IHE are apt to be more sensitive to certain effects of stockpile aging.

The size and weight of warheads might also have to be increased. We have learned from experience that larger systems are less prone to parametric design changes and, for this reason, would be expected to be less prone to the effects of stockpile aging. The increased size and weight of the warhead could also generate the need for larger missile systems.

Similarly, the more nuclear material, such as plutonium and tritium, that a weapon contains, the more robust it normally is to parametric changes and consequently to the effects of stockpile aging. This could entail the use of more nuclear material initially or could lead to more frequent change of tritium components (tritium has a 12-year half-life), with increased operational costs.

Other improvements that might be relinquished include certain built-in security and construction features that allow weapons, such as EPWs, artillery shells, and lay-down bombs, to withstand extremely high accelerations and decelerations. The latter features could affect the operation of a nuclear warhead and could be the source of uncertainty in the event of a stockpile aging problem.

Conclusions

Nuclear weapons research and development, supported by nuclear testing, is essential to maintaining the credibility of the U.S. nuclear deterrent. Because the global strategic balance is constantly changing, new weapon systems must be developed to ensure the safety, security, survivability, and military effectiveness of the deterrent. The DOE weapons design laboratories have the dual responsibility of ensuring that the weapons currently in the stockpile are safe and reliable and of developing warheads for new systems as they are needed.

Nuclear testing is essential if the laboratories are to meet this responsibility successfully. Nonnuclear tests and computer simulations are very valuable tools, but there is no substitute for the experimental data from nuclear tests. In many instances, weapons scientists must rely on technical judgment to make decisions regarding problems that arise in the stockpile, in recommending changes in weapon systems, and in developing new warheads—judgment that can only derive from and be refined with actual data from nuclear tests. The importance of nuclear testing was illustrated by our experiences with the test moratorium of 1958–1961. Without nuclear testing, deterrence would still be based on nuclear weapons but at significantly higher cost and with greater uncertainty.

Key Words: Comprehensive Test Ban (CTB); earth-penetrating warhead (EPW); ground-launched cruise missile (GLCM); high explosive—conventional, insensitive, TATB; laser—Nova; nuclear directed-energy weapon (NDEW); nuclear weapon—design, research and development, stockpile aging, testing; small intercontinental ballistic missile (SICBM); Strategic Defense Initiative (SDI).

Notes and References

1. The May 1983 and August 1986 issues of *Energy and Technology Review* (UCRL-52000-83-5 and UCRL-52000-86-8) describe many of the Laboratory's efforts in treaty verification and arms control.